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Shunt Analysis in Solar Cells – Electro-Optical Classification and High Resolution Defect Diagnostics

S. Großer*, D. Lausch, M. Werner, S. Swatek, M. Mergner,
V. Naumann, C. Hagendorf

Fraunhofer Center for Silicon Photovoltaics CSP, Walter-Hülse-Straße 1, 06120 Halle, Germany

Abstract

The investigation on solar cells defects plays an important role in the optimization of processes and solar cell efficiencies, since based on the information about the causes and mechanisms of these defects will help to develop solutions for avoiding these defects. Contaminations or structural damages can limit and reduce the solar cell efficiency. The focus of this work is to present a methodology of a classification and target preparation for small defect analysis. As a high-resolution electro-optical method Dark Lock-In Thermography (DLIT) was applied for the localization and voltage-dependent classification of electrical defects (e.g. shunts) on solar cells. The local dark current-voltage (I - V) properties are measured after separation of distinct single defects on solar cells fragments (~ 1 cm²). Different types of shunts are distinguished based on their I - V characteristics. A detailed root cause analysis was done on the microscopic scale using reverse biased electroluminescence (ReBEL) combined with an optical microscopy (μ ReBEL). After defect localization on a sub- μ m scale, target preparation has been performed by means of Focused Ion Beam (FIB) techniques. Process-induced structural defect properties are revealed by means of Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) with Nanospot Energy Diffractive X-ray (EDX) analysis. In the present work, we will present the methodology of classification, preparation and identification of local shunts. The analysis will show that this procedure of defect diagnostic based on electro-optical classification parameters and target preparation is a suitable method to detect contamination sources and to optimize production processes.

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* Corresponding author

E-mail address: stephan.grosser@csp.fraunhofer.de

1. Introduction

Material- as well as process-induced shunts are of major importance for reliability and longtime stability of multicrystalline silicon (mc-Si) solar cells and modules since local heating due to shunts may lead to an irreversible damage or even to a destruction of solar modules. Therefore it is necessary to understand the causes and the mechanisms of electrical shunts in solar cell technologies. Lots of studies were done by various authors to overcome these problems [1-6]. But the cause and occurrence of shunts in solar cells are manifold and not fully understood yet. Because of that further shunt analysis and research have to be performed to support and to enable technological solutions for reducing breakdown issues in solar cells. For this sophisticated analysis methods for investigating shunts on a module, cell and microscopic level must be provided.

In the current work, we present a comprehensive strategy for shunt diagnostics ranging from cell level localization by means of dark Lock-in Thermography (DLIT) [7], Reverse Biased Electroluminescence (ReBEL) [3] and mini-cell preparation up to advanced electron microscopy micro structure diagnostics.

2. Electro-optical detection and classification

The first step of the defect classification has to be the analysis of the whole cell. Established and well known experimental methods have been used like DLIT, EL or ReBEL. By applying a voltage to a solar cell defects, inhomogeneity or even cell cracks are visible. Usually, solar cells have defects originating from the bulk material or by non-perfect production conditions. In this contribution a mc-Si solar cell was used to demonstrate the procedure of defect classification, preparation and target preparation. Using DLIT a defect free cell should appear dark by an applied reverse bias under their intrinsic breakdown voltage of about -60 V. However, this is not the case in real solar cells. The amplitude image (derived from the amplitude signal of the DLIT measurement) is in approximation proportional to the dissipated power caused by the applied voltage. This power dissipation leads to a local increase of the temperature, which can be monitored very well by the LIT-technique. Examples of local shunts are presented in Fig. 1. Two DLIT measurements of the same cell area are done at different reverse voltages. In (a) the voltage was -4 V and in (b) -10 V. The defect marked as B appears for both voltages similar due to different scales of the amplitude image. In contrast to this the power dissipation of defect A is much higher in (b) than in (a).

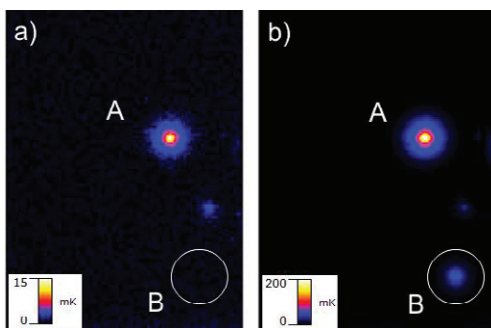


Fig. 1. DLIT amplitude images at different voltages. (a) $V = -4$ V and (b) $V = -10$ V

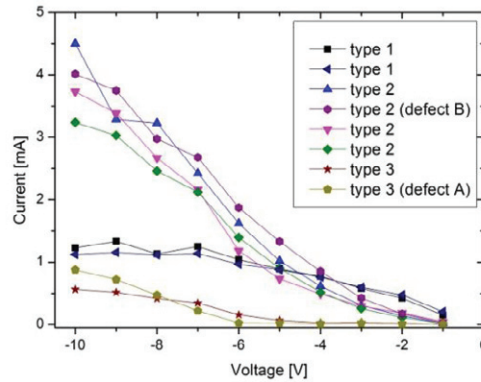


Fig. 2. I - V curves of several single defects on the same solar cell calculated by analysing voltage dependent DLIT measurements

For further classification or differentiation of the defects we have been conducted DLIT measurements at different voltages. By analysis of the measurements the local current flowing through the shunts can be approximated when the series resistance of the cell is not too high. Therefore, the current density is proportional to the DLIT amplitude signal. By using the assumption that the power is proportional to the DLIT amplitude signal the local power can be calculated.

By integrating the DLIT amplitude signal of a defect area and dividing it by the DLIT amplitude signal of the whole cell the fraction of the current can be derived approximately. Quantitative evaluation of shunts in solar cells by Lock-in Thermography is described in detail by Breitenstein et al. [9]. The analysis as a classification tool has been conducted for several defects on a mc-Si cell and the derived defect I - V curves are shown in Fig. 2. Three different characteristics can be deduced. Type 1 shows an clear ohmic behaviour since the current is proportional to the voltage. Type 2 and type 3 exhibit diode-like properties. However, type 3 shows a higher pre-breakdown voltage than type 2. A detailed and more intensive study of shunt and pre-breakdown mechanisms cannot be given here but are well described elsewhere [1-6].

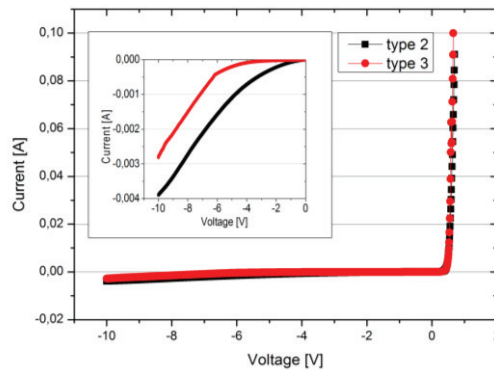


Fig. 3. Dark I - V curves of two cell fragments with different classes of defects (type 2 and 3) obtained by four-point probe measurements

The found defects types 1 are clearly ohmic shunts. Since type 2 appear already below -5 V we assume that in terms of the literature notation [1, 8] these defect type is equal to the TYPE I pre-breakdown investigated by Lausch et al. [5]. They identified these defects by SEM/EDX mappings as Al-particles which have been on the wafer surface before antireflection coating. Defect type 3 exhibits more the TYPE II (in the literature notation [1]) like behaviour. For comparison to the DLIT derived classification solar cell fragments were made by mechanical separation. Two different defect types (2, 3) each prepared on a single fragment has been investigated. A four-point probe measurement was used to cross-check the classification results shown in Fig. 2. For type 2 a dark I - V curve with a diode-like behaviour, which results in an ohmic behaviour for voltages over -5V, is found. The ohmic behaviour at higher voltages could be due to a serial resistance effect. Type 3 shows a pre-breakdown curve which blocks the reverse current for voltages lower than -3 V. This is in agreement with the data in Fig. 2. At forward bias both cell fragments exhibit the same behaviour dominated by the characteristic of the solar cell device.

3. Local detection methods and cross-section analysis

3.1. DLIT and μ ReBEL

Defect A which shows a diode-like I - V characteristic has been studied as an example into more detail. Using DLIT the solar cell fragment with defect A was measured again at higher magnification presented in Fig. 4 (a). It can be seen that the power is dissipated on a single point. The halo in the amplitude picture is due to the high heat conduction in the silicon wafer. Within the halo a grid finger of the solar cell can be seen because of the grid finger's lower emissivity with respect to the adjacent area. Further details cannot be resolved because of the limitation in DLIT by the blurring of the signal. To localize the defect more precisely we used the μ ReBEL technique [3] displayed in Fig. 4 (b).

The inset in Fig. 4 shows the μ ReBEL image at -10 V of defect A. One can see that defect A is localized to several micrometres. It seems to be the combination of two small point defects close by each other. We used the precise localisation to identify the position on the surface by correlation of microscopic images, μ ReBEL images and placing marks on the cell fragment, close to defect structures.

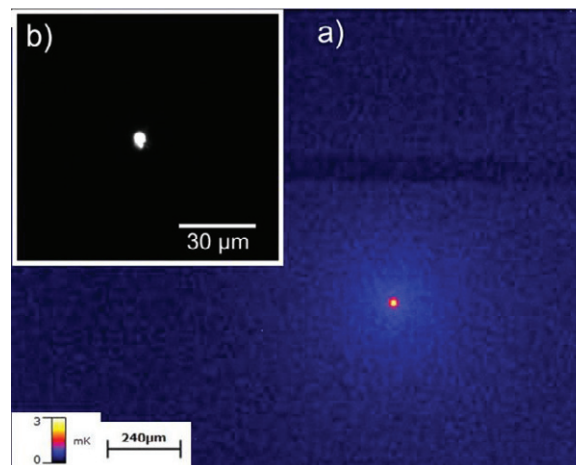


Fig. 4. (a) DLIT amplitude ($V = -6.3$ V; $I = 0.71$ mA) and (b) μ ReBEL ($V = -10$ V) image of defect A with high local resolution

3.2. Focused Ion Beam (FIB) technique and Transmission Electron Microscopy (TEM)

In a SEM a small defect cannot be easily distinguished from local electrically inactive contaminations/particles on the surface or when the defect is buried. Using the local detection method described before a defect can be found in the SEM quite fast. μ ReBEL data are correlated with SEM micrographs to identify the position. Additionally, electron-beam induced current (EBIC) measurements can be done to detect areas where the space charge region is disturbed by defects. Hence, particles on the sample surface lower the EBIC signal as well. Therefore, the EBIC signal needs to be correlated to electro-optical data as well. In this case defect A can be identified as a particle on the surface. A cross-section of the particle has been made by using focused ion beam (FIB) technique. Fig. 5 (a) shows a SEM micrograph of a cross-section (lamella structure for TEM-analysis) of the particle, which is covered by a Pt-layer for protection during FIB preparation. Two small particles can be seen which exhibit buried voids. Due to the cross-section preparation the irregular shaped single particle was divided into two single adjacent particles. The silicon surface is contacted only at some points. TEM reveals more details of the local microstructure. Fig. 5 (b) shows a TEM micrograph of an area where the particle has touched the surface. The Pt-protection layer appears dark and holes appear bright. Underneath the Pt-protection a homogeneous layer can be seen which covers the particle on top. The particle seems to be in direct contact with the silicon surface. To characterize the chemical composition of the microstructure nanospot EDX has been performed. The defect structure consists of a particle which shows strong aluminum and oxygen signals. Silicon and nitrogen signals reveal that the layer on top of the aluminum oxide particle is most likely a silicon nitride antireflective coating. At the interface between the particle and the silicon surface no nitrogen signals can be found in the EDX-spectra which correspond with the assumption concerning the covering layer before. One can conclude that the found oxidized aluminum particle (or aluminum oxide particle) has been on the surface before the deposition of the antireflective coating.

The observed structure reveals properties of Type I pre-breakdown described by Lausch et al. [5]. Particularly, the observed EDX mappings at the cross-section show similar structures and results. However, in contrast to the assigned TYPE I the defect A shows a higher pre-breakdown voltage as described by Lausch et al. [5]. The reason for this could be a slightly different barrier between the stain

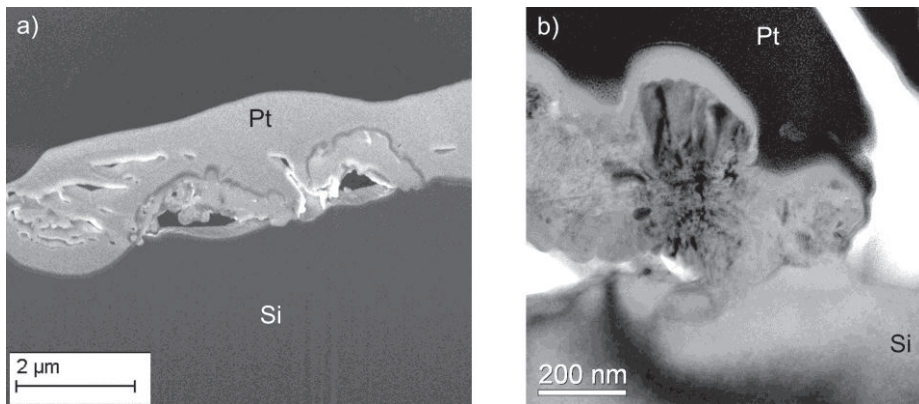


Fig. 5. Microstructure of defect A: (a) SEM micrograph of a FIB cross-section and (b) TEM micrograph

and the surface or another doping situation. Nevertheless, further investigations are needed to describe the distinct effects of aluminium oxide on the pre-breakdown voltage.

4. Summary

We presented a study of a methodology for defect classification by their electro-optical characteristics and a microstructural root cause analysis. Using different I-V characteristics derived from voltage dependent DLIT measurements local defects were assigned to classes depending on their ohmic and/or diode-like properties. In the shown example three types of defects were found. The observed type 3 which shows a diode-like behavior has been studied into more detail to show a typical approach for nano-scaled investigations. We used DLIT and μ ReBEL techniques to determine the position of the local pre-breakdown site in the range of some micrometers. Using the localization we could identify the position on the sample surface in SEM and prepared a cross-section and a TEM-lamella for further microstructural investigations. We found out that the defect consists of aluminum and oxygen and has been on the surface before deposition of the antireflective coating. This is in good agreement to the actual literature knowledge [5].

The presented methodology of classification and target preparation is a great advantage for optimizing solar cell production processes by a structured analysis which helps to identify contamination sources applicable for various solar cell techniques and concepts.

Acknowledgements

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References

- [1] Breitenstein O, Bauer J, Bothe K, Kwapil W, Lausch D, Rau U, Schmidt J, Schneemann M, Schubert MC, Wagner J-M, Warta W. Understanding Junction Breakdown in Multicrystalline Solar Cells, *J. Appl. Phys.* 2011; **109**: 071101.
- [2] Bauer J, Wagner J-M, Lotnyk A, Blumtritt H, Lim B, Schmidt J, Breitenstein O. Hot Spots in Multicrystalline Silicon Solar Cells: Avalanche Breakdown due to Etch Pits, *Phys. Status Solidi RRL* 2009; **3**: 40-42.
- [3] Lausch D, Petter K, von Wenckstern H, Grundmann M. Correlation of Pre-Breakdown Sites and Bulk Defects in Multicrystalline Silicon Solar Cells, *Phys. Status Solidi RRL* 2009; **3**:70-72.
- [4] Wagner M, Gründig-Wendrock B, Palinginis P, Knopf C. Shunts, Diode Breakdown and High Reverse Currents in Multicrystalline Silicon Solar Cells, in: *Proc. 24th EUPVSEC*, Hamburg, Germany, 2009; 2028-2031.
- [5] Lausch D, Petter K, Bakowskie R, Czekalle C, Lenzner J, von Wenckstern H, Grundmann M. Identification of Pre-breakdown Mechanism of Silicon Solar Cells at Low Reverse Voltages, *Appl. Phys. Lett.* 2010; **97**: 073506
- [6] Kwapil W, Gundel P, Schubert MC, Heinz FD, Warta W, Weber ER, Goetzberger A, Martinez-Criado G. Observation of Metal Precipitates at Breakdown Sites in Multicrystalline Silicon Solar Cells, *Appl. Phys. Lett.* 2009; **95**: 232113.
- [7] Quantitative shunt investigations on solar cells by lock-in thermography. 12th Workshop on Crystalline Solar Cell Materials and Processes 2002; 125-135
- [8] Bauer J, Ph.D. thesis, Martin-Luther-University Halle-Wittenberg (2009)
- [9] Breitenstein O, Rakotoniaina J P, Rifai M H A. Quantitative evaluation of shunts in solar cells by lock-in thermography, *Prog. Photovolt: Res. Appl.* 2003; **11**: 515-526